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THE APPLICATION OF SALT AND WATER BALANCES TO QUANTIFY CAUSES OF THE DRYLAND SALINITY PROBLEM IN VICTORIA

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Abstract: The magnitude of the effect of land use changes applied by agricultural development to the cycles of salt and water are examined using a mass balance model approach. Historical data sets for catchments in the northern slopes of Victoria are used to obtain an estimate of the increase in groundwater recharge. For catchments with recognised soil or stream salinity problems the recharge increase is about 20 mm yr^{-1}; catchments with water-logging problems have a recharge increase in the range 20 to 80 mm yr^{-1}. These increases are a relatively small proportion of rainfall and similar in magnitude to increases in other parts of southern Australia with similar problems. The characteristic time for equilibration of salt input and loss is of order 1000 years in salt-affected catchments. A mass balance for the 4183 km^2 highlands segment of the Loddon River to Laanecoorie Weir suggests that increased recharge in non-irrigated agricultural land has contributed 60×10^6 m^3 yr^{-1} of water to the development of current groundwater conditions in the Loddon Plain.

Where the mass balance approach is inappropriate, simple equilibrium recharge/discharge models may be useful, particularly as a first approximation, even when empirical estimates of evaporation are included. Discharge estimation using the groundwater flux to the seepage area is preferred when the soil surface is not continuously wet. This method gave an estimate for average recharge of 17 mm yr^{-1} for a salt-affected catchment near Kamarooka.

In southwest Victoria about 50% of mean stream discharge is brackish or saline. In the Wannon River basin, an analysis using a published data set showed that catchments dominated by agricultural land use exceeded forested catchments in salt loss by a factor of 4. Historical data sets appear to be available which, if used in the mass balance approach, could provide an estimate of the increase in recharge for catchments in the southwest region. An advantage of the mass balance approach is that a reasonable approximation can be obtained fairly quickly of the quantities of water and salt involved in recognised processes. This allows the relative importance of each process to be determined as a guide to development of reclamation strategies.

The hydrologic cycle provides a conceptual framework in which the dynamic processes associated with input, transfer and output of water in an environmental system can be analysed. The water cycle transports salts as the solute load in the various phases of the cycle. In natural systems the flows of water and salt are usually steady state flows, at least in a time scale of order 1000 years. The consequence of man's activities, particularly by making drastic changes in land use, is to inject a perturbation into the natural regime which may require a time scale of tens to thousands of years for a new steady state flow condition to be achieved. In most cases it is expected that the re-establishment of steady state flow will have a longer time scale for salt than for water due to the differences in storage characteristics.

The dryland salinity problem has been recognised as a consequence of man-induced changes in the magnitude of some components of the hydrologic cycle. Even if not fully understood, the dynamic nature of the problem is recognised through the observation that the area of salinised land is increasing in practically all locations.

The need to quantify the magnitude of the induced changes in the hydrologic cycle has motivated a number of studies in southern Australia in recent years. The objective of one such study in the Northern Slopes of Victoria during 1981 was to quantify the principal mechanisms of secondary salinisation as a basic requirement for establishing criteria for reclamation strategies. This paper indicates the magnitude of changes to components of the hydrologic cycle consequent to agricultural development. Details of the methods used in the study are reported elsewhere (Williamson 1983). As a corollary, it is intended to demonstrate that conceptually simple models can be useful in establishing the order of magnitude of the causes of dryland salinity problems.

THE HYDROLOGIC DISTURBANCE

The hydrologic regime existing in Australia before European settlement had probably achieved steady-state conditions following the major climatic change about 6000 years B.P. Agricultural development has provided a major perturbation to that pristine system (Holmes 1971). The development of a saline seep involves a transient increase in salt loss. If no further land use changes are made, the rate of salt loss could be expected to decay to the pristine level at equilibrium with the rate of salt input from atmospheric deposition and rock weathering processes. The deterioration of water quality in rivers and the secondary salinisation of soils are examples of the consequence of the adjustment necessary to achieve a new steady state. By determining the nature and magnitude of the perturbation applied by agriculture to the cycles of water and salt, it is possible to examine whether the perturbating factors may be altered either to their magnitude under the pristine condition or to a level

which places an acceptable impact on the environment as the new steady-state condition establishes. In the latter case, a significant factor would be the extension of the transient flow phase.

The qualitative description of the causes of secondary salinisation following agricultural development was first published in Victoria over 20 years ago (Cope 1958) and in Western Australia over 60 years ago (Wood 1924). It is only in the last 10 years that studies have adequately quantified the problem (e.g. Peck & Hurle 1973) to allow a rational approach to be made in establishing reclamation strategies.

From the qualitative understanding, it has been established that secondary salinisation requires a source of soluble salt, a source of water, and the mechanism for redistribution of salt. The importance of the groundwater system and the changes applied to it by agricultural development have been recognised through the association of groundwater seepage with salinisation (Williamson & Bettenay 1979, Jenkin 1981).

Consequently, change in groundwater recharge and mass of stored salt which may be redistributed in the regolith need to be quantified. Factors requiring quantification to establish the mechanism for salt redistribution include increase in the leaching rate of stored salt and characteristics of the solute flow and flow path in aquifers. Changes in hydraulic gradient, changes in cross-sectional area of groundwater flow (though not necessarily associated with a change in solute flux), and structural changes of the solute flow path such as in the development of preferred channels following root decay, may contribute to an increase in seepage. An estimation of the increase in groundwater recharge may be made by determining the difference in the sum of evaporation plus surface run-off for pre- and post-development phases. However, using any of the currently available methods for quantifying catchment-scale evaporation, the error term for the estimate of groundwater recharge could be of the same magnitude as the recharge itself. It is preferable, therefore, to make a direct measurement of recharge or of a response by the groundwater system to the change in recharge such as increased discharge or groundwater level change.

APPLICATION OF A MASS BALANCE MODEL

Simple models applying the water balance principle may provide an estimate of recharge to an aquifer system. Results obtained are sensitive to the relationship of actual to potential evaporation, and when comparing changes in land use, the effect of these changes on surface run-off. More sophisticated models which use explicit mathematical descriptions of the hydrologic processes in a catchment are a significant improvement on the simple model for quantifying unknown fluxes such as recharge. Aston and Dunin (1980) achieved an estimate of annual streamflow with an error of 10% using the distributed hydrologic model SHOLSIM. However, the application of these models in many problems is limited by the inability to satisfy their data needs. The historical data sets acquired in the course of routine monitoring of basic hydrologic characteristics by government agencies, and the compliance type data, though simple and often incomplete, do present a data base often appropriate to use in simpler models.

The combination of the conservation equations for both salt and water provides a set of equations which lead to the determination of the groundwater discharge in a catchment for pre-clearing and present land use conditions. The method is given in detail by Williamson (1983) and follows closely that used by Peck and Hurle (1973). Essentially, salt concentration of present groundwater discharge to a stream is determined by a mass balance analysis of streamflow in which available data are measured values for streamflow volume and salt concentration, an estimate for groundwater discharge volume, and salt concentration of surface run-off. Determination of the pristine groundwater discharge uses a simple mass balance where salt input by rainfall equals salt output by run-off and groundwater discharge. If it is assumed that the salt concentration of groundwater discharge is two or more orders of magnitude larger than the salt concentration of run-off, and that pristine run-off volume is a small proportion of the rainfall, it is possible to obtain an estimate of pristine groundwater discharge using a mass balance equation. Average saltfall in rain is assumed to be the same for both pristine and current land use periods. The salt concentration of groundwater discharge determined for the present agricultural condition is assumed also to be unchanged from the pristine situation. Groundwater discharge from unit area of agricultural land may be estimated given the fraction of the catchment having that type of land use. Groundwater recharge and discharge are equated by assuming that equilibrium conditions for waterflow in the catchment have been achieved where agricultural development commenced over 50 years ago. It is not axiomatic that saltflow from the catchment has reached a steady-state also.

The mass balance model uses available historical data for quantity and quality of rainfall and streamflow (run-off plus groundwater discharge). In addition a number of assumptions other than those already mentioned, must be applied: 1. The annual groundwater discharge component of present streamflow may be estimated as the summation of monthly baseflow using daily rainfall and streamflow records in a simple baseflow separation approach. The method tends to underestimate total groundwater discharge by not making any allowance for evaporation from the stream during summer or enhanced discharge associated with rainfall events. The error is unlikely to exceed 25% when calculated concentrations of groundwater discharge are compared with measured concentrations of streamflow during periods of low flow or of groundwaters in the few boreholes near surface drainage lines. 2. The deep drainage component of the water balance is assumed to be zero, the salinity of run-off is assumed equal to rainfall salinity and, in the pre-clearing situation, rainfall salt input is equated to salt output in streamflow. It is also assumed that the annual salt contribution from

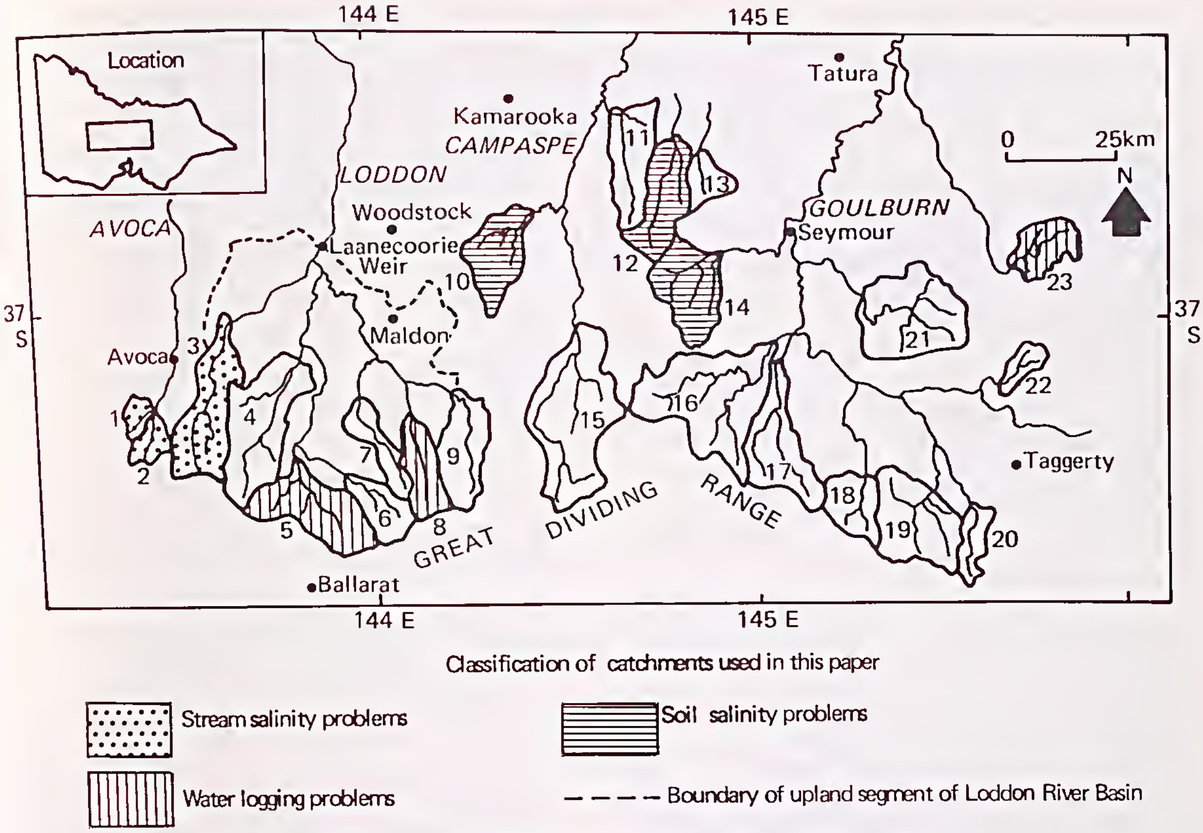

Fig. 1—Location of catchments used in mass balance studies.

weathering of country rock is negligible compared with salt input by rainfall. Salt storage was determined using a trapezoidal integration of salt content for discrete samples over the total depth (usually to country rock) of the sampled profile.

The chloride ion concentration was used as the measure of salinity, primarily because circulation of the ion in the hydrologic cycle is largely through physical processes (Hem 1970). For streamflow, chloride concentration was determined by correlation with electrical conductivity, the correlation coefficients exceeding 0.98 for the 4 major streams for which data were available.

This mass balance model does not pretend to achieve any real depth in conceptualising the hydrologic system as it responds to the change in land use. Further application of the understanding of processes which cause the changes in groundwater recharge and discharge, both in space and time, should be fruitful in developing a more dynamic model which nevertheless avoids the data demands and computational extent of many deterministic models. Despite the simplifying aspects of this model, a measure of average response is achieved even if no dynamic characteristics are elucidated.

CATCHMENT RECHARGE

The mass balance model was applied to 23 catchments within the Goulburn, Campaspe, Loddon and Avoca River basins shown in Fig. 1. Data on stream-flow quantity and quality were supplied by the State Rivers and Water Supply Commission for the 16 year period from 1965 to 1980. Chloride input in rainfall was estimated using a correlation with distance from the coast in a south-west direction which was established using a data set obtained during a statewide sampling program between 1974 and 1977 by the Department of Agriculture. Land use was determined from Land Conservation Council Maps, and median rainfall isohyets were drawn using rainfall station records of the Bureau of Meteorology which exceeded 50 years duration. The Department of Minerals and Energy core sampling activities provided samples of 36 bore holes for salt storage determination. Results of soil salt contents to about 6 m obtained by the Soil Conservation Authority in several catchments supplemented and supported the deeper borehole data.

The catchments are all within the uplands between the alluvial plain in the north and the Great Dividing Range to the south (see Fig. 1). This is a medium winter rainfall zone, the median rainfall decreasing from 1500 mm yr^{-1} in the southeast to 450 mm yr^{-1} in the northwest of the region, and pan evaporation increasing from 1000 mm yr^{-1} in the south to 1500 mm yr^{-1} for the most northerly catchments. The general climatic description is Mediterranean type, 77% of the rainfall

TABLE 1
RAINFALL, STREAMFLOW AND CALCULATED GROUNDWATER DISCHARGE FOR CATCHMENTS DOMINATED BY HIGH STREAM SALINITY, SOIL SALTING AND WATER LOGGING PROBLEMS (RESPECTIVELY) IN THE NORTHERN SLOPES OF VICTORIA

Flow and discharge data are averages for 1965-1980 period.

Catchment No	Catchment Name	Land Use[1]	Rainfall mm yr^{-1}	Streamflow mm yr^{-1}	Groundwater Discharge to Streams (mm yr^{-1}) Present	Pre-clearing	Agric Land	Seepage Increase for Agric. Land mm yr^{-1}
1	Glenlogie	1.0	620	73	22	2	22	20
2	Amphitheatre	0.9	660	58	16	2	18	16
3	Norwood	0.9	580	59	7	1	8	7[2]
10	Axe Creek	0.7	650	69	13	1	19	17
14	Major's Creek	0.5	570	59	5	1	9	8[2]
12	Colbinabbin	0.8	530	45	3	1	4	3[2]
5	Clunes	0.8	720	85	25	9	29	20
8	Yandoit	0.6	850	158	50	17	77	60
23	Polly McQuinn	0.9	990	318	141	69	149	80

[1] Data are the proportion of the catchment cleared for agriculture.
[2] Catchments where the output of water from the catchment by groundwater flow beneath the stream gauging station is considered an important factor though estimated to be less than the groundwater discharge component in streamflow.

occurring in the May to October period resulting in a cool wet winter and a hot dry summer.

Results of the calculated groundwater discharge component of streamflow for pristine and present land use conditions in a number of catchments are given in Table 1. The table is in three sections representing catchments with stream salinity (Catchments 1, 2, 3), soil salinity (Catchments 10, 12, 14) or water-logging (Catchments 5, 8, and 23) problems associated with the development of more than half the catchment for agriculture. For 3 catchments (3, 12, and 14), the subsurface groundwater discharge is considered to be an important contribution to total groundwater discharge. Data are not available to calculate the contribution. Using estimates of the magnitude of the hydraulic parameters it is suggested that subsurface groundwater discharge from any of the catchments will be less than the groundwater discharge via streamflow, even where deep leads are involved.

The seepage increase for the agricultural land segment of each catchment is the measure of groundwater recharge increase due to agricultural development. For the 6 catchments with recognised soil or stream salinity problems associated with dryland agriculture, recharge

TABLE 2
SALTFLOW, STREAM SALINITY, SALT STORAGE AND CHARACTERISTIC TIME TO EQUILIBRIUM FOR SELECTED CATCHMENTS IN THE NORTHERN SLOPES OF VICTORIA

Flow and salinity data are averages for 1965-1980 period.

Catchment No	Catchment Name	Present Stream Salinity mg Cl^-L^{-1}	Saltflow in stream g $Cl^-m^{-2}yr^{-1}$	Saltflow to Saltfall ratio	Estimated Mean Salt Store g Cl^-m^{-2}	Net Salt Loss g $Cl^-m^{-2}yr^{-1}$	Characteristic Time to Equilibrium years	Stream Concentration at Equilibrium mg Cl^-L^{-1}
1	Glenlogie	455	34	13.4	No data	31	—	34
2	Amphitheatre	448	26	10.4	No data	24	—	43
3	Norwood	258	16	6.5	23×10^3	13[1]	1200	40
10	Axe Creek	276	19	10.0	32×10^3	17	1700	28
14	Major's Creek	134	8	4.5	No data	6[1]	—	32
12	Colbinabbin	151	7	3.8	22×10^3	5[1]	2700	40
5	Clunes	94	8	3.0	2×10^3	5	60	32
8	Yandoit	47	7.5	3.1	2×10^3	5	300	15
23	Polly McQuinn	11	3.5	2.2	No data	2	—	5

[1] Does not include salt loss in subsurface drainage, which if included, would reduce the characteristic time to equilibrium.

increase is of order 20 mm yr^{-1}. This is about 3% or less of the median annual rainfall, and about 1% of the annual average pan evaporation. For the catchments with water logging problems, the estimated recharge increase due to agriculture is in the range 20 to 80 mm yr^{-1}, being up to 8% of either median annual rainfall or average annual pan evaporation. In the Polly McQuinn catchment, the seepage-induced water logging is particularly noticeable even at quite high positions in the landscape. Nevertheless, in all cases, the increase in recharge following agricultural development is a relatively small proportion of the rainfall, and is in the range of estimates given for interception difference between forest and grassland (Blake 1975, Holmes & Wronski 1981). The range of recharge increase is similar to that obtained by Peck and Hurle (1973) of from 23 to 65 mm yr^{-1} in a similar rainfall range in southwest Australia. In southeast South Australia drainage measurements using a lysimeter (Holmes & Colville, 1970) and a steady-state environmental chloride and tritium concentration method (Allison & Hughes 1978) gave results for mean recharge in the range from 50 mm yr^{-1} for a sand over heavy clay to 250 mm yr^{-1} for free draining skeletal soils all vegetated by improved pasture. Allison and Forth (1982) have estimated that the present day recharge in southeastern South Australia is approximately 2.5 times the pristine levels.

SALT BALANCE AND EQUILIBRIUM TIME

The average (flow-weighted) stream salinity for the 1965-80 period (Table 2) reflects the effect of agriculture on stream water quality. The saltflow to saltfall ratio indicates that there is a net export of salt from all catchments. It is a characteristic of catchments with salinity problems that the output/input ratio for salt exceeds 5 when an estimate of the subsurface saltflow component is included in the salt output.

The characteristic time to equilibrium is the time taken for the enhanced groundwater discharge rate to decrease the salt store in the regolith to a new equilibrium level, identified by the re-establishment of a balance between salt input and output. Assuming that the present saltflow conditions are maintained, the characteristic time to equilibrium for catchments with salinity problems is of order 1000 years (Table 2). For the catchments with waterlogging problems, the characteristic time is less, being a period of tens to hundreds of years. At equilibrium the salt concentration of streamflow would be lower than for the pristine environment due to a higher volume of stream flow in the new equilibrium state. Peck & Hurle (1973) estimated characteristic times of order 100 years for catchments with dryland salinity problems in southwest Australia.

The results obtained in the northern slopes catchments suggest that an average salt storage greater than 20×10^3 g $Cl^- m^{-2}$ is a characteristic of the regolith in catchments with dryland salinity problems (Table 2). The thickness of weathered material above the country rock is in the range 10 to 100 m for the 36 sampled boreholes located either within or adjacent to catchments used in the study. The basalt profiles (dominant in Clunes) contain the lowest salt storage except when they overlie siltstones, slates or weathered granites which probably restrict drainage and promote salt accumulation. The higher salt storages are associated with the alluvial profiles (usually clay) and Silurian mudstones. There is a general increase in stored salt with decreasing rainfall indicating a degree of climatic control. The salt storage is similar in magnitude to that found in southwest Australia where the range is from 6×10^3 to 60×10^3 g $Cl^- m^{-2}$ for a rainfall zone from 1400 to 500 mm yr^{-1} (Stokes *et al.* 1980). The importance of quantifying salt storage for the full depth of the weathered profile becomes obvious when the hydrologic significance of seepage from aquifers in the weathered zone is accepted as the primary process in dryland salinisation (Jenkin 1981). The salt stored in the arable surface zone (to say 1 m), even if saline conditions have established, is unlikely to exceed 5% of the total profile salt storage.

REGIONAL MASS BALANCE—LODDON RIVER DRAINAGE BASIN

Seven catchments in the study set occupy 1880 km^2 in the upland segment of the Loddon River basin which forms the catchment to Laanecoorie Reservoir (Fig. 1). Numerous branches of the Loddon Deep Lead trunk system occur within the catchment and converge at a point about 11 km northeast of Laanecoorie Weir before continuing under the Loddon Plain. The drainage by the lead system should be included when quantifying the water and salt balance for the upland region. Data given by Macumber (1978b) on the dimensions and hydraulic conductivity of the trunk lead system near Woodstock, and an assumed hydraulic gradient of 0.01 were used to calculate the waterflow in the lead from the upland catchment. The portion of this flow which originates in the Avoca basin is unlikely to be greater than 25% if the cross-section of this tributary lead is used as the basis of estimation. The salinity of the groundwater is of order 1000 mg TDS L^{-1} (about 350 mg $Cl^- L^{-1}$) near Bridgewater (Macumber 1978a).

Average annual saltflow and waterflow for the 4183 km^2 catchment to Laanecoorie Weir have been determined for the period 1965-1980, and are given in Table 3. The estimate of saltflow and waterflow contributed by the lower segment of the catchment is obtained by difference, assuming that the river is not influent to the groundwater system, between the upper segment and Laanecoorie Weir. The regional mass balance quantifies the contribution by agricultural land use in the highlands to streamflow and aquifer development in the Loddon Plain.

The results in Table 3 also show that the deep lead system contributes about 10% of the waterflow from the highlands to the plain, but about 25% of the salt. The salt input to the catchment in rainfall is estimated at 2.3 g $Cl^- m^{-2} yr^{-1}$ to give a saltflow to saltfall ratio of 3.7, indicating that there is a net export of salt from the highlands to the plain. The salt loading delivered to the

TABLE 3
SALT AND WATER FLOW FOR THE CATCHMENT OF THE LAANECOORIE RESERVOIR WHICH FORMS THE HIGHLANDS SEGMENT OF THE LODDON RIVER DRAINAGE BASIN

	Area	Waterflow		Saltflow	
	km^2	$m^3\ yr^{-1}$	$mm\ yr^{-1}$	tonnes $Cl^- yr^{-1}$	g $Cl^- m^{-2} yr^{-1}$
SURFACE WATER SYSTEM					
Upper Segment (7 catchments)	1880	167×10^6	89	16.5×10^3	8.8
Lower Segment	2303	59×10^6	24	10.4×10^3	4.5
Whole Catchment	4183	226×10^6	53	26.9×10^3	6.4
DEEP LEAD SYSTEM					
Flow at Woodstock	4183	25×10^6	6	8.7×10^3	2.1
COMBINED SURFACE AND DEEP LEAD SYSTEMS					
Total	4183	251×10^6	59	35.6×10^3	8.5

plain as a consequence of man's activities is about 26×10^3 tonnes $Cl^-\ yr^{-1}$ (about 73×10^3 tonnes TDS yr^{-1}).

An average recharge increase for agricultural land of 21 mm yr^{-1} has been calculated using the mass balance model for the 7 catchments forming the upper segment, and is equivalent to $29 \times 10^6\ m^3\ yr^{-1}$. The streamflow records at Laanecoorie Weir cannot be used to estimate the groundwater discharge to the stream due to the effect of the reservoir on the stream hydrograph. The stream quality data show an average concentration during low flows of about 400 mg $Cl^-\ L^{-1}$. This was used in the Peck and Hurle (1973) version of the mass balance model to obtain an estimate for average recharge increase of 18 mm yr^{-1} to the 3292 km^2 of agricultural land in the Laanecoorie catchment. This is equivalent to $59 \times 10^6\ m^3\ yr^{-1}$. Therefore the average recharge increase for agricultural land in the lower segment is about 16 mm yr^{-1}, equivalent to $30 \times 10^6\ m^3\ yr^{-1}$. This is accepted as a reasonable estimate. Further, it can be shown from the simplified pristine mass balance that the estimate for pristine groundwater discharge is about 4 mm yr^{-1} or about $17 \times 10^6\ m^3\ yr^{-1}$ which is 70% of the present estimate for flow in the trunk deep lead.

These results suggest that there is a groundwater contribution of about $60 \times 10^6\ m^3\ yr^{-1}$ by agriculture to the flow from the highlands to the Loddon Plain. As a natural drainage system, the trunk deep lead is apparently functioning at maximum capacity, with the balance of the increase in recharge (about $35 \times 10^6\ m^3\ yr^{-1}$) becoming output to the surface drainage lines. The contribution that this excess water from the highlands may have on salinisation of non-irrigated farmland in the Loddon Plain is dependent on the geohydrologic features which may direct flow toward the soil surface along preferred channels or provide conditions for development of extensive areas of shallow groundwater. Irrigated agriculture has been considered to be a significant contributor to the development of the current groundwater conditions in the Loddon Plain (Macumber 1978b). The mass balance results suggest that increases in recharge due to non-irrigated agriculture in the highlands should be considered also as an important source of water and salt for the development of groundwater problems in the Loddon Plain.

A SIMPLE EQUILIBRIUM RECHARGE-DISCHARGE MODEL

The assumption of a steady-state flow condition for water in a catchment provides a basis for estimating average recharge. Particularly in catchments with low relief, the loss of water by evaporation from saline seepages can be expected to dominate and exceed the discharge to a stream. Use of the combined salt and water balance model may be quite inappropriate or may be limited by a lack of a reasonable length of a stream flow record as in the case of catchments 11, 12 and 13.

The water balance condition that discharge equals recharge assumes that the steady-state has been achieved following the hydrologic perturbation applied by agricultural development. Having established the area of the groundwater discharge zone (A_s), the area of recharge (A_c) can be assumed to be that part of the catchment which is not a discharge zone. The average recharge (R_c) is given by the simple equation

$$R_c = \frac{A_s G}{A_c}$$

The groundwater discharge (G) may be estimated as the sum of seepage flow (F_x) to a stream and evaporation from the seep area (E_s) estimated as a fraction (f) of pan evaporation (E_p). Alternatively, the discharge (G) may be estimated using the physical characteristics of the flow path of groundwater to the seepage surface in an appropriate flux equation.

Where there is no apparent seepage flow across the soil surface, care is needed in the assumption that evaporation from the discharge area is at the potential rate. For any particular seepage area, use of evaporation from the seep, horizontal flow to the seep in the groundwater system, and an analysis of vertical flow to the seepage area, provide independent checks on the estimate of average current discharge.

This input-output model was used to estimate the recharge for a catchment of 2090 ha near Kamarooka. A saline seepage zone of 390 ha has developed at the upland edge of the alluvial plain, the recharge area being in gentle hills formed on Ordovician sedimentary bedrock strata (Dyson & Jenkin 1981). This system contains aquifers in the weathered zone at 15 to 20 m depth and in an underlying less weathered fractured and jointed zone. Within the saline seepage zone, piezometer nests indicate that the gradient for flow is toward the soil surface. The deeper jointed aquifer appears to be the primary flow path for water from the recharge area to the seepage area. There is no defined surface drainage line associated with the saline seepage area.

To use the evaporation approach to estimate recharge, the following parameter values were obtained: $A_s = 390$ ha, $A_c = 2090\text{-}390 = 1700$ ha, $F_x = 0$, $E_s = 0.6\ E_p = 0.6 \times 1350 = 810$ mm yr^{-1}, leading to the annual recharge estimate of 185 mm.

The hydraulic properties of the seepage area provide an alternate data set. The vertical flow path includes an alluvial clay zone whose average hydraulic conductivity is known (0.01 m day^{-1}, see Dyson & Jenkin 1981). The piezometer nests provide measurement of the average hydraulic gradient (0.02). Applying Darcy's Law, the discharge flux density for the seepage area, G, is 0.073 m yr^{-1}. The estimate of catchment recharge is therefore calculated as 17 mm yr^{-1} with the variation in hydraulic parameters suggesting that the recharge rate lies in the range 10 to 40 mm yr^{-1} (P. Dyson, personal communication). The rainfall for this catchment is 450 mm yr^{-1} which suggests that the recharge estimate of 186 mm, using the evaporation approach, is too large. The absence of surface flow of seepage water from the saline area and the hydraulic control on the vertical flux of water (Dyson & Jenkin 1981) further suggest that it is inappropriate to use a measure of potential evaporation in this case. The alternate groundwater flux approach provides an acceptable recharge estimate of order 20 mm yr^{-1}.

The application of this input-output model may also be appropriate in areas such as the Mallee. In many situations, the simple approach may provide not only an estimate of recharge, but also a quantification of fluxes in the hydrologic system which would assist identification of the significant flow paths for water and salt.

POTENTIAL FOR APPLICATION OF MASS BALANCE MODELS

Dryland salinity has tended to focus on the consequence for soil resources, with attention given primarily to those catchments adjacent to the River Murray or having tributaries to the river. These have flow of high volume and generally of good quality. In western Victoria, the effect which agricultural development has had on increasing recharge of groundwater results in increased saline seepage to the soil surface and to streams in particular. The loss in quality of water resources usually has a greater economic cost than the degradation of soil resources.

The 9 river basins west of Melbourne and south of the Great Dividing Range contribute 14% of the surface water resources of Victoria. Flow in 3 basins is classified as marginal quality, and in another 4 as brackish or saline (Water Resources Council 1980). About 50% of the mean discharge of 3.3×10^9 m^3 yr^{-1} by the rivers exceeds 1000 mg TDS L^{-1}. The Avoca River is the only other river basin in Victoria whose flow is similarly classified (Water Resources Council 1980).

Table 4 provides data comparing the yield of brackish and saline water resources in Victoria with those in southwest Western Australia where the impact of dryland salinisation on water quality is of major con-

TABLE 4

COMPARISON OF YIELD OF BRACKISH AND SALINE WATER RESOURCES FOR VICTORIA AND SOUTHWEST WESTERN AUSTRALIA

Location	Area km^2	Yield of Brackish and Saline Water $m^3\ km^{-2}yr^{-1}$	Average Total Water Yield $m^3\ km^{-2}yr^{-1}$
VICTORIA			
South-West Rivers (Basins 30 to 38)	43 900	37×10^3	76×10^3
All River Basins	245 860	7×10^3	95×10^3
WESTERN AUSTRALIA			
South-West Rivers (Basins 3 to 14, 16)	71 200	24×10^3	80×10^3
South-West Coast Drainage Division	314 500	8×10^3	21×10^3

Sources: Water Resources Council, 1980; Brown, 1983.

cern (Sadler & Williams 1981). The 13 river basins in southwest Western Australia have potential for water resource development and lie within 280 km of the coast. The southwest Coast Drainage Division includes the wheatbelt and other intensive agricultural developments in southwest Western Australia. Whilst recognising the difference in geographical factors of the regions being compared, there is significance in the similarity of yields of low quality water resources. The concern for the low quality of about 30% of the water resources in southwest Western Australia has promoted extensive investigations into the causes and management of the salinisation. With 50% of the water resources of southwest Victoria of inferior quality, there is need, apparently, for increased activity in examining the causes and possible management options in the region.

The economic and social impact of degraded surface water resources is diminished when alternative reliable sources, particularly groundwater, are available. Increasing demand on water resources for industrial and domestic use by places such as Geelong and Portland could direct attention to the causes of the poor quality of surface water. In addition to saline seepage resulting from clearing, two major drainage schemes contribute to the salinity of the Barwon River (Gutteridge, Haskins, & Davey 1979). Saline seepage from areas of dryland agriculture has reduced the water quality to stock supply, at best, in all but the more mountainous upper reaches of both the Glenelg and Wannon Rivers (Anon 1968). A survey of the Otway Soil Conservation District has identified 57 km^2 of salinised soil (J. Duff, pers. comm.) in the Lake Corangamite and Barwon River drainage basins.

Re-working the data for the Wannon River originally presented by Currey (1970), with additional data on land use in each of the 8 catchments examined, provides some quantification of the effect of agricultural land use in the region. For forested catchments, the saltflow to saltfall ratio was 2.4 with mean stream salinity in the range 45 to 100 mg TDS L^{-1}. For catchments dominated by agricultural land use, the saltflow to saltfall ratio was 13 with mean stream salinity in the range 750 to 1500 mg TDS L^{-1}. For the 4500 km^2 catchment of the Wannon River to Sandford, the salt loading to the river by agriculture was about 140×10^3 tonnes TDS yr^{-1}. Assuming that salt storage was similar to the Northern Slopes, the characteristic time to equilibrium would be of the order of hundreds of years. Land development of 160 km^2 in the catchment of the Glenelg River above Rocklands Reservoir was not approved following an enquiry in 1968 which estimated that water quality in the reservoir would become unacceptable (Anon 1968).

The historical data sets, providing streamflow quantity and, at least, first order water quality information, appear to be adequate in the southwest of Victoria (AWRC 1978) to apply the mass balance model. It is expected that quantification of salt and water fluxes will confirm that land use change has caused the apparent degradation of the water resources of the region. As for the Northern Slopes, the results should assist in establishing appropriate strategies for reclamation.

DISCUSSION AND CONCLUSIONS

Although the simple water and salt balance approach can provide an interpretation of the consequences of land use change in quantitative terms, and assist in developing criteria for reclamation strategies, more detailed studies are needed to reach a practical and effective control of the increase in recharge. The major advantage of the simpler model approach is that one can obtain fairly quickly a reasonable approximation to the quantities involved in recognised processes. In addition, it is possible to identify the relative importance of each process and establish where more detailed studies should be most effective. For example, the recharge estimate obtained using the simple mass balance model is only an average for the agricultural land in the catchment including discharge areas. Further quantitative studies are needed to identify the variation in recharge rate in a catchment and determine the relative input to total catchment recharge volume of each contributing segment.

It is a reasonable criticism of the models demonstrated in this paper to say that there is unused understanding of the processes in the hydrologic cycle which could be applied to broaden the conceptualisation included in the models. Improvements could include giving the model a two or three dimensional structure, and incorporating concepts which remove the more sensitive but important assumptions. The use of simple models should help to identify the system parameters whose measurement is essential. Further development of the simpler model type should be beneficial for those who have limited data sets or who lack the resources to obtain the intensive data sets for the more sophisticated deterministic or stochastic models.

The effect of agricultural development has been shown to produce an increase in recharge to groundwater of about 20 mm yr^{-1} where soil and stream salinity problems have developed. With the characteristic time to a new equilibrium in saltflow of order 1000 years, there is need to establish how land management may be modified to reduce the rate of redistribution of salt to surface soils and streams. In the higher rainfall catchments water logging appears to be the significant effect of agricultural development. Though not apparently leading to salinisation, productivity of the land is reduced. The highlands segment of the Loddon River Basin has an average recharge increase also of order 20 mm yr^{-1} which apparently exceeds the capacity of the natural drainage by the deep lead system. The importance of this contribution to the high water table and salinisation problems in the Loddon Plains needs to be compared with the contribution by irrigated agriculture.

Whilst the problem of soil salinisation associated with dryland agriculture in north and central Victoria has received increasing attention, the effect of dryland agriculture on surface water quality in the southwest of the state appears to have been ignored. About 50% of stream discharge exceeds 1000 mg TDS L^{-1}. Application of the mass balance model could assist in quantifying the cause and providing a basis for determining appropriate management for reclamation.

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REFERENCES

Allison, G. B. & Forth, J. R., 1982. Estimation of historical groundwater recharge rate. *Aust. J. Soil Res.* 20: 255-259.

Allison, G. B. & Hughes, M. W., 1978. The use of environmental chloride and tritium to estimate total recharge to an unconfined aquifer. *Aust. J. Soil Res.* 16: 181-195.

Anon., 1968. Report to the Land Utilisation Advisory Council on Land in the Grampians area. Prepared by a study group on land in the Glenelg region (F. R. Gibbons, Chairman). 98 pp.

Aston, A. R. & Dunin, F. X., 1980. Land-use hydrology: Shoalhaven, New South Wales. *J. Hydrol.* 48: 71-87.

AWRC, 1978. *Stream gauging information, Australia.* 4th Edition. Australian Water Resources Council, Department of National Development, Australian Government Publishing Service, Canberra.

Blake, G. J., 1975. The interception process. In *Prediction in Catchment Hydrology*, T. G. Chapman & F. X. Dunin, eds, Australian Academy of Science, Canberra, A.C.T., 59-82.

Brown, J. A. H., 1983. *Australia's surface water resources: An assessment of the quantity and quality of Australia's surface water resources.* WATER 2000 Consultant Report Volume 1. Australian Government Publishing Service, Canberra.

Cope, F., 1958. *Catchment salting in Victoria.* Publication T.S.1, Soil Conservation Authority, Melbourne, 88 pp.

Currey, D. T., 1970. Lake Systems, Western Victoria. *Aust. Soc. Limnology Bull.* 3: 1-13.

Dyson, P. R. & Jenkin, J. J., 1981. *Hydrological characteristics of soils relevant to dryland salting in central Victoria.* Mimeographed Report, Soil Conservation Authority, Melbourne, 51 pp.

Gutteridge, Haskins & Davey Pty Ltd, 1979. *Barwon River Water Management Study—Public discussion document.* Prepared for Geelong Water Works and Sewerage Trust and Geelong Regional Commission, November 1979, 58 pp.

Hem, J. D., 1970. *Study and interpretation of the chemical characteristics of natural water.* 2nd Edition. U.S. Geological Survey Water-Supply Paper 1473, Washington D.C.

Holmes, J. W., 1971. Salinity and the hydrologic cycle. In *Salinity and Water Use*, T. Talsma & J. R. Philip, eds, Macmillan, London, 25-40.

Holmes, J. W. & Colville, J. S., 1970. Grassland hydrology in a karstic region of South Australia. *J. Hydrol.* 10: 38-58.

Holmes, J. W. & Wronski, E. B., 1981. The influence of plant communities upon the hydrology of catchments. *Agric. Water Manage.* 4: 19-34.

Jenkin, J. J., 1981. Terrain, groundwater and secondary salinity in Victoria, Australia. *Agric. Water Manage.* 4: 143-171.

Macumber, P. G., 1978a. Hydrological equilibrium in the southern Murray Basin, Victoria. In *The Hydrogeology of the Riverine Plain of south east Australia*, R. R. Storrier & I. D. Kelly, eds, Australian Society of Soil Science, Riverina Branch, Wagga Wagga, 67-88.

Macumber, P. G., 1978b. Hydrologic change in the Loddon Basin: the influence of groundwater dynamics on surface processes. *Proc. R. Soc. Vict.* 90: 125-138.

Peck, A. J. & Hurle, D. H., 1973. Chloride balance of some farmed and forested catchments in south western Australia. *Water Resour. Res.* 9: 648-657.

Sadler, B. S. & Williams, P. J., 1981. The evolution of a regional approach to salinity management in Western Australia. *Agric. Water Manage.* 4: 353-381.

Stokes, R. A., Stone, K. A. & Loh, I. C., 1980. *Summary of soil salt storage characteristics in the northern Darling Range.* Water Resources Technical Note 84, Public Works Department, Western Australia, 11 pp.

Water Resources Council, 1980. *Review of Victoria's water resources and utilisation, Part 1, General Outline.* Water Resources Council, Ministry of Water Resources and Water Supply, Victoria, 110 pp.

Williamson, D. R. & Bettenay, E., 1979. Agricultural land use and its effects on catchment output of salt and water-evidence from southern Australia. *Prog. Wat. Tech.* 11: 463-480.

Williamson, D. R., 1983. *Quantification of salt and water balances to guide regional strategies for reclamation of dryland salinisation.* Groundwater Research Technical Paper (in preparation), CSIRO, Australia.

Wood, W. E., 1924. Increase of salt in soil and streams following the destruction of the native vegetation. *J. R. Soc. W. Aust.* 10: 35-47.